

# QUARKONIUM AND CHARM HADRONS : NEW RESULTS ON SPECTROSCOPY IN BABAR

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We report on recent results in spectroscopy from *BABAR*. This includes the discovery of a new  $\Lambda_c$  baryon, detailed studies of the  $D_{sJ}^*(2317)^+$ ,  $D_{sJ}(2460)^+$ ,  $X(3872)$  and  $Y(4260)$  particles and the first measurement of hadronic non- $B\bar{B}$  decays of the  $\Upsilon(4S)$  meson.

## 1 *BABAR*

The *BABAR* detector is described in detail in a prior publication<sup>1</sup>.

## 2 Charm Baryon Spectroscopy

The current particle assignment by the Particle Data Group<sup>2</sup> is assigned indirectly rather than being based on angular analysis. The  $\Lambda_c(2785)$  and  $\Lambda_c(2880)$  states<sup>3</sup> are only listed as single or double asterisk (respectively) as they have not yet been confirmed.

In studying the  $D^0p$  spectra *BABAR* has observed two charm baryons<sup>4</sup>, the  $\Lambda_c(2880)$  and the  $\Lambda_c(2940)$ . The data sample in this study was  $288 \text{ fb}^{-1}$ . The  $D^0$  was found from its decay to either  $K^-\pi^+$  or  $K^-\pi^+\pi^-\pi^+$ . No signal for these particles was seen in the  $D^+p$  mode which rules out a  $\Sigma_c$  states.

The observation of these particles in this channel rules out some other non- $\Lambda_c$  interpretations<sup>5</sup>;  $\Sigma_{c2}(\frac{3}{2}, \frac{5}{2})$ ,  $\Lambda'_{c1}(\frac{3}{2})$  and  $\Lambda'_{c2}(\frac{3}{2}, \frac{5}{2})$ .

The first of these is the  $\Lambda_c(2880)$ , confirming CLEO's discovery<sup>3</sup>. The particle's parameters found in this analysis are;

$$m = [ 2881.9 \pm 0.1 \text{ (stat.)} \pm 0.5 \text{ (syst.)} ] \text{ MeV}/c^2$$

$$\Gamma = [ 5.8 \pm 1.5 \text{ (stat.)} \pm 1.1 \text{ (syst.)} ] \text{ MeV} .$$

Table 1: A summary of the combined mass and width results. For the masses, the first quoted uncertainty is statistical and the second is systematic. The limits on the intrinsic width  $\Gamma$  are at 95% CL.

Particle	Mass (MeV/ $c^2$ )	$\Gamma$ (MeV)
$D_{sJ}^*(2317)^+$	$2319.6 \pm 0.2 \pm 1.4$	$< 3.8$
$D_{sJ}(2460)^+$	$2460.1 \pm 0.2 \pm 0.8$	$< 3.5$
$D_{s1}(2536)^+$	$2534.6 \pm 0.3 \pm 0.7$	$< 2.5$

A new baryon has been discovered with the properties;

$$m = [ 2939.8 \pm 1.3 \text{ (stat.)} \pm 1.0 \text{ (syst.)} ] \text{ MeV}/c^2$$

$$\Gamma = [ 17.5 \pm 5.2 \text{ (stat.)} \pm 5.9 \text{ (syst.)} ] \text{ MeV} .$$

This state has been given the name  $\Lambda_c(2940)^+$ . There is no evidence of doubly-charged partners in the  $D^+p$  spectrum.

### 3 Charm Meson Spectroscopy

Current theory of treating  $c\bar{s}$  system like the hydrogen atom (with one heavy and one light element) has been fairly successful. Prior to 2003 this theory had postulated many particles that were later observed as expected. A few expected states were not observed and this was ascribed to their predicted large widths.

The  $D_{sJ}^*(2317)^+$  was discovered by *BABAR*<sup>6</sup>. CLEO published<sup>7</sup> the discovery of the  $D_{sJ}(2460)^+$ .

An extensive study of decays to  $D_s^+$  plus one or two particles of the types  $\pi^\pm$ ,  $\pi^0$  or  $\gamma$  has been carried out<sup>8</sup> looking at  $232\text{fb}^{-1}$  of data.

The  $D_s^+$  was reconstructed from only  $K^+K^-\pi^+$  decays. Furthermore to reduce background, only certain intermediate states were allowed: either a  $\phi(1020)$  could be reconstructed from the  $K^+K^-$  or a  $\bar{K}^*(892)$  from  $K^-\pi^+$ .

Only three decay modes are measured (the rest only have upper limits reported in this analysis). The ratio of the measured branching fractions are;

$$\frac{\mathcal{B}(D_{sJ}(2460)^+ \rightarrow D_s^+ \gamma)}{\mathcal{B}(D_{sJ}(2460)^+ \rightarrow D_s^+ \pi^0 \gamma)} = 0.337 \pm 0.036 \pm 0.038$$

$$\frac{\mathcal{B}(D_{sJ}(2460)^+ \rightarrow D_s^+ \pi^+ \pi^-)}{\mathcal{B}(D_{sJ}(2460)^+ \rightarrow D_s^+ \pi^0 \gamma)} = 0.077 \pm 0.013 \pm 0.008$$

The decays seen are consistent with both particles being P-wave  $c\bar{s}$  mesons with the  $D_{sJ}^*(2317)^+$  being  $0^+$  and the  $D_{sJ}(2460)^+$  being  $1^+$  states. The particle properties measured in this analysis are shown in Table 1. It should be noted that no intrinsic width is measured.

No evidence was found for doubly-charged or neutral partners of the  $D_{sJ}^*(2317)^+$ . This deficit disfavors some molecule interpretations of these states.

The fully reconstructed B sample was used to also study twelve decay modes of neutral and charged B mesons of the form  $D_{s(J)}^{(*)} D^{(*)}$ . In this sample the properties of the the B mesons are well known due to all decay products of one of the B mesons being measured. This analysis used 230 million  $B\bar{B}$  pairs<sup>9</sup>.

All decay products of one of the D mesons are also measured, the other D could decay to anything and is represented as  $D_X$ , its mass and momenta inferred by kinematics. The mass spectra of the  $D_X$  system is studied in each of the modes to determine absolute branching fractions.

Using previously published<sup>10</sup> *BABAR* study of the branching fraction for  $B \rightarrow D_{sJ}(2460)^+ D^{(*)}$  it is possible to determine some absolute branching fractions;

$$\begin{aligned}
B(D_{sJ}(2460)^+ \rightarrow D_s^{*+}\pi^0) &= (56 \pm 13_{\text{stat.}} \pm 9_{\text{syst.}}) \% \\
B(D_{sJ}(2460)^+ \rightarrow D_s^+\gamma) &= (16 \pm 4_{\text{stat.}} \pm 3_{\text{syst.}}) \%
\end{aligned}$$

We therefore know that the  $D_{sJ}(2460)^+$  decays via a photon or a  $\pi^0$  emission to a  $D_s^{(*)+}$  ( $72 \pm 19$ )% of the time. Also known from branching fraction ratios reported earlier in this section together with this result that approximately another 4% emit a pair of charged pions while decaying to a  $D_s^+$ .

#### 4 Charmonium Spectroscopy

There are many models for Charmonium spectroscopy that predict as yet unseen particles<sup>11</sup>. Some of these may be the recently observed X(3872) and Y(4260) states.

The X(3872) particle was discovered by Belle<sup>12</sup> and confirmed by BABAR<sup>13</sup>. It is unknown if it is a  $c\bar{c}$  pair, diquark-antidiquark pair or a  $D^0\bar{D}^{*0}$  molecule.

The diquark model would predict that the X(3872) is actually two amplitudes of a nonet, one visible via charged and other via neutral B mesons decays. The predicted mass difference of the  $X_u$  and  $X_d$  states is  $7 \pm 2 \text{ MeV}/c^2$ . The difference has been measured<sup>14</sup> to be  $2.7 \pm 1.3 \pm 0.2 \text{ MeV}/c^2$ . This is consistent with both the prediction and zero.

Some molecules models predict that the ration of these branching fractions should be less than 10%. The measurement shows the ratio to be between 0.13 and 1.10 at the 90% confidence level, so those models are disfavoured.

Belle has reported evidence<sup>15</sup> of the decay  $X(3872) \rightarrow J/\psi\gamma$  in B meson decays. An analysis has been done using 287 million  $B\bar{B}$  decays to confirm this. The following branching fraction was also measured to validate signal extraction method and is found to agree with the the Particle Data Group value;

$$B(B^+ \rightarrow \chi_{c1}K^+) = (5.6 \pm 0.2 \pm 0.7) \times 10^{-4}$$

The analysis finds  $19.2 \pm 5.7$  events and a product branching fraction of;

$$B(B^+ \rightarrow X(3872)K^+, X(3872) \rightarrow J/\psi\gamma) = (3.4 \pm 1.0 \pm 0.3) \times 10^{-6}$$

The observation of this mode implies that the X(3872) is a C=+1 state. The partial width ratio has also been measured to be;

$$\frac{\Gamma(X(3872) \rightarrow J/\psi\gamma)}{\Gamma(X(3872) \rightarrow J/\psi\pi^+\pi^-)} = 0.34 \pm 0.14$$

$232\text{fb}^{-1}$  of initial state radiation (ISR) data has been studied looking for the X(3872) but no evidence was found. This unsuccessful search for X(3872) resulted in the discovery of the Y(4260)<sup>16</sup>. This state has been confirmed by CLEO<sup>17</sup>.

A study has been carried out on 232 million  $B\bar{B}$  decays<sup>14</sup>. This study shows a consistent feature with the discovery spectra and measures a product branching fraction of;

$$B(B^- \rightarrow Y(4260)K^-, Y(4260) \rightarrow J/\psi\pi^+\pi^-) = (2.0 \pm 0.7 \pm 0.2) \times 10^{-5}$$

An analysis of  $232\text{fb}^{-1}$  of ISR data using the final state  $K^+K^-\pi^+\pi^-$  has been carried out, in this analysis the ISR photon was observed. Events are selected where the kaon pair comes from a  $\phi$  to provide a confidence limit (CL);

$$B(Y(4260) \rightarrow \phi\pi^+\pi^-) \cdot \Gamma_{ee}^Y < 0.4\text{eV at } 90\% \text{ CL}$$

A recent *BABAR* result<sup>16</sup> can be use to obtain the ratio of branching fractions;

$$\frac{B(Y(4260) \rightarrow \phi\pi^+\pi^-)}{B(Y(4260) \rightarrow J/\psi\pi^+\pi^-)} < 0.102 \text{ at } 90\% \text{ CL}$$

The glueball hypothesis predicts<sup>18</sup> these to be equal, therefore it is disfavoured.

## 5 Bottomonium Spectroscopy

Decays of the  $\Upsilon$  states above the  $B\bar{B}$  have been primarily to that state. *BABAR* has now measured some non- $B\bar{B}$  hadronic decays of the  $\Upsilon(4S)$ .

This analysis<sup>19</sup> used  $(230.0 \pm 2.5) \times 10^6 \Upsilon(4S)$  decays, which corresponds to  $211\text{fb}^{-1}$  of on-peak data. As a cross check another  $22\text{fb}^{-1}$  of off-peak data (approximately 40MeV below the  $\Upsilon(4S)$  peak) was searched for for any indications of  $\Upsilon(4S)$  decays and none were found.

The decays being searched for are  $\Upsilon(4S) \rightarrow \Upsilon(nS)\pi^+\pi^-$ , with  $n=1,2$ . The  $\Upsilon(nS)$  states are reconstructed from oppositely charged pairs of electrons or muons. However, due to high background from Bhabha events only the muon decays are used in the measurement. The electron sample is use as a cross check.

The branching fractions obtained by using the Particle Data Group's averages for  $B(\Upsilon(nS) \rightarrow \mu^+\mu^-)$ ;

$$\begin{aligned} B(\Upsilon(4S) \rightarrow \Upsilon(1S)\pi^+\pi^-) &= (0.90 \pm 0.15) \times 10^{-4} \\ B(\Upsilon(4S) \rightarrow \Upsilon(2S)\pi^+\pi^-) &= (1.29 \pm 0.32) \times 10^{-4} \end{aligned}$$

## 6 Summary

A new charmed baryon has been observed. In addition, for the first time a decay of a charm baryon to a non-charm baryon has been measured. Many enhancements to the knowledge of the  $D_{sJ}^*(2317)^+$ ,  $D_{sJ}(2460)^+$ ,  $X(3872)$  and  $Y(4260)$  particles have been accomplished. We have reported on the first measurement of hadronic non- $B\bar{B}$  decays of the  $\Upsilon(4S)$  meson.

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